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Bridging Local Ecological Knowledge and Pastoral Agroecosystems: A Conceptual Framework from North-Central Patagonia

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ABSTRACT

In arid Patagonia, Argentina (central plateau of Chubut), family subsistence farming depends almost exclusively on native vegetation and Local Ecological Knowledge (LEK). This work proposes the Pastoral Agroecosystem Framework (PAF), a new conceptual framework based on empirical evidence that explains the contribution of LEK to the functioning of pastoral systems, offering analytical tools for other pastoral systems in arid and semi-arid regions of the world. Through ethnobiological methodology based on 20 semi-structured interviews with rural herders, 72 forage plant species belonging to 27 botanical families were recorded, of which 87.5% are native. The valuation of species depends on the roles attributed to them within the pastoral system: milk production, sustaining animals during critical periods, differential use of environments, and resource availability throughout the year. Key functional components were also identified: strategic environments such as wetlands (mallines), species used during scarcity events, and adaptive management practices linked to forage resource dynamics. The results reveal LEK as a higher-order operational component that, through adaptive management decisions, identifies, regulates, and articulates its functional components, thereby operating the pastoral system and promoting emergent properties such as productivity, stability, and resilience. The proposed PAF allows us to understand that the joint care of native biodiversity, wetlands, and local knowledge constitutes a fundamental pillar for the resilience of these socio-ecosystems in the face of desertification, climate change, and other transformations.

Keywords: ethnobotany; local ecological knowledge; pastoral systems; arid Patagonia; forage plants; resilience.

1. Introduction

Subsistence sheep and goat herding is the livelihood of numerous pastoral populations worldwide (FAO, 2001). These family farming systems (FFS) are based on Local Ecological Knowledge (LEK), defined as the set of knowledge, practices, values, and beliefs, culturally transmitted, about the relationships between living beings and their environment (Berkes, 2012; Toledo & Barrera-Bassols, 2008). In particular, the raising, care, and management of animals by rural herders involve networks of sociability between humans and non-humans, where plant populations and spatiality play a prominent role in sustaining flocks and human communities over time (Lans et al., 2007; Lema, 2014; Nyamanga et al., 2008; Pieroni et al., 2004; Tabuti et al., 2003; Viegi, 2003). Thus, LEK is a

constitutive part of these networks, giving rise to the agrobiodiversity (ABD) of FFS (Wesuls & Lang, 2010).

In the arid and semi-arid zones of Patagonia, the LEK of FFS encompasses knowledge about plants, animals, soils, climatic cycles, and productive management, in a context of high environmental variability that sustains rural life (Castillo et al., 2020; Richeri et al., 2013a,b; Ladio & Lozada, 2004; 2009; Grimaldi et al., 2024). According to its situated character (Nygren, 1999), this knowledge is rooted in territories forged through historical processes of subalternization of family farming systems whose boundaries are diffuse (Ejarque 2016, 2017). Therefore, LEK linked to FFS is not a static or ahistorical knowledge devoid of disputes and power relations, but rather constitutes a dynamic, heterogeneous, and fragmented repertoire that is recreated in contexts of resistance and cultural marginalization, configuring a local biocultural heritage.

Currently, various processes of social and environmental change, intensified by global change, accelerate ecosystem deterioration, deepen expulsive migratory models that threaten FFS, ABD, and associated LEK (Ladio 2017; FAO 2001). Particularly, in arid and semi-arid regions of Patagonia, processes of erosion of this knowledge can compromise the resilience of pastoral systems. Given this panorama, ethnoecological approaches offer an interesting framework to address the challenges posed by global change: bottom-up perspectives and their situated fieldwork allow capturing the complexity of local narratives (Ladio, 2017), facilitating a horizontal dialogue between different knowledge systems for the co-design of contextually viable management strategies (Albuquerque et al., 2024; Ladio, 2017). In particular, in arid zone grasslands with high environmental variability, LEK about forage plants has been highlighted as a central aspect for adaptive management decision-making in contexts of high environmental variability (Wesuls & Lang, 2010).

Worldwide, various studies have documented LEK about forage plants in pastoral systems of arid and semi-arid zones, providing concrete lessons on adaptive management, an approach that fosters continuous learning about socio-ecosystems and allows acting despite uncertainty, reducing it through practice itself — what has been called "learning by doing" (Allen & Garmestani, 2015). For example, Naah (2019) documented how West African agro-pastoralists distinguish between herbaceous forage (preferred by cattle in the rainy season) and woody forage (preferred by goats and sheep in the dry season), showing that aridity influences the number of valuation criteria, while Wario et al. (2015) showed that Borana herders classify grasslands into grazing units that correlate with forage abundance, and Samuels et al. (2016) found that herded grazing allows dietary diversification, whereas free grazing reduces resilience to droughts. In Argentina, previous studies have documented knowledge of forage plants in peasant communities of the semi-arid Chaco and Formosa, also highlighting the importance of woody species as a strategic resource (Márquez et al., 2024; Muiño 2010; Scarpa 2007). Likewise, recent works have pointed out the need to simultaneously consider multiple ecological and use attributes to understand the forage value of species (Jiménez-Escobar et al., 2026). These approaches suggest that the valuation of forage resources involves more complex dimensions than nutritional quality or animal preference considered in isolation. Finally, a global review covering Africa, Asia, and Europe (Sharifian et al., 2023) synthesized 35 indicators and 10 principles of LEK about forages, such as the valuation of "scarcity fodder" and spatial adaptation.

Together, these studies show that LEK about forages includes dynamic (seasonality, scarcity), spatial (habitat classification, mobility), and functional criteria. However, they have concentrated on Africa,

Asia, and Europe, or in other regions of Argentina, without including the southern cone of South America. This gap limits the understanding of local adaptive strategies and the possibility of extracting lessons about LEK associated with forage biodiversity for management in arid and semi-arid zones that can contribute to guiding ethnoecologically based development strategies. This work proposes the Pastoral Agroecosystem Framework (PAF), a new conceptual framework based on empirical evidence from Patagonia (central plateau of Chubut, Argentina), offered as an analytical tool to understand other pastoral systems in arid and semi-arid regions of the world.

Hypothesis and objectives

It is hypothesized that the inhabitants have built, throughout their history, a deep connection with the forage plant resource, which is maintained and recreated dynamically in the face of environmental variability and within a framework of structural vulnerability. The objectives of this work are: 1) To document the diversity of plant species that herders recognize as forage, identifying their botanical composition, biogeographic origin, and forage classes. 2) To identify the local criteria for forage valuation and the functional roles assigned to different species within the pastoral system, considering dimensions such as seasonality, grazing environments, plant parts consumed, and scarcity situations. 3) To propose and describe the Pastoral Agroecosystem Framework (PAF), based on empirical evidence gathered in the central plateau of Chubut.

2. Materials and Methods

2.1 Study area. The work was carried out in the semi-arid region of the north-central plateau of Chubut, Argentine Patagonia, in the localities of Sierra Rosada, Sierra Ventana, and El Escorial (43°05'46" S, 68°33'25" W) (Figure 1). The climate is dry and cold during much of the year (mean annual temperature of 11.3°C and mean annual precipitation of 174 mm), exposing inhabitants to harsh conditions at certain times of the year (annual average of 98 frost days). Strong westerly winds are one of the characteristic climatic features of the region (León et al. 1998).

The vegetation corresponds to the Patagonian phytogeographic province (Cabrera 1976), where medium-height shrubby-grassy steppes predominate, characterized by dwarf cushion shrubs, scarce grasses, and low total cover (less than 50%, Paruelo et al., 2005). The upper stratum (up to 2 m) including Lycium spp., Neltuma spp., Schinus johnstonii, and Atriplex lampa, and a lower stratum (< 1 m) including Mulinum spinosum, Chuquiraga avellanedae, and Acaena splendens. Grasses include Pappostipa speciosa, P. humilis, Poa lanuginosa, and Jarava neaei. Exotic species such as Rosa rubiginosa and Bromus tectorum also grow in the region (León et al. 1998). Soils are poor in organic matter, with abundant sands and erosion pavements that become exposed when the wind removes fine materials, leaving Patagonian gravels uncovered; these erosion pavements are characteristic indicators of wind erosion processes in the region (Bouza et al., 2007; Rostagno & del Valle, 1988).

Mallines are wetlands associated with permanent or semi-permanent watercourses, of high livestock interest due to their moist soil and abundance of palatable pastures (Lloyd, 2002). Saline mallines present a community dominated by junquillo (Juncus balticus) and pelo de chancho (Distichlis spicata) (Lloyd, 2002).

In arid and semi-arid Patagonia, livestock activity has a historical trajectory that includes the adoption of the horse and seasonal transhumance (Coronato 2011; Ejarque 2016). At the end of the 19th century, state appropriation displaced indigenous populations, imposing extensive livestock farming oriented toward wool export and fencing lands (Ejarque 2016). Subalternized sectors were confined

to marginal lands, developing subsistence herding and a situated construction of LEK (Ejarque 2017; Hermosilla 2014; Castillo et al. 2020; Richeri et al. 2013a,b).

2.2 Socio-cultural characterization.

The people who inhabit the region and engage in herding activity are of Mapuche/Tehuelche and/or Creole origin, and reside in small-scale livestock establishments (≈2500 ha), with great distances between them and from the nearest towns or cities. Their subsistence economy combines goat and sheep herding (with flocks of ≈200 animals on average) with hunting, family horticulture, firewood collection, and the sale of forest resources (Coronato 2015; Richeri et al. 2013a). Production is extensive and at fixed stocking rates; fields are not usually subdivided into paddocks and, although some families are landowners, most are in irregular tenure situations (family succession), which generates conflicts and limits access to credit. Profitability is very low due to mortality from predators, extreme climatic events (droughts, snowstorms, volcanic ash), and desertification (Iglesias et al. 2015; Travaini et al. 2000; von Thüngen 2014). This low productive efficiency is combined with extra-economic factors that sustain the activity, such as attachment to the land and a strong sheep-farming culture, which demands policies oriented toward rural "good living" (Galer 2023; Iglesias et al. 2015). In the territory, larger-scale livestock units (≥6 leagues) with differentiated management (rotations, paddocks) also coexist, although currently most are depopulated or subproductive. These family farming systems (FFS) are characterized by social reproduction under dignified conditions, the centrality of family labor, and the construction of situated knowledge linked to the reproduction of life (FONAF, 2006; Birgi et al. 2020). Agrobiodiversity (ABD) — understood as the set of genetic resources and associated sociocultural knowledge — constitutes the material and symbolic basis of FFS, sustaining nutritional diversification, food security, and food sovereignty of families (Galer et al. 2017; 2023), and configuring diverse productive landscapes.

2.3 Ethnobiological work

Four field campaigns (2012-2015) were carried out in the localities of Sierra Rosada, Sierra Ventana, and El Escorial. Sampling was exhaustive: 87% of inhabited establishments were visited (20 of 23), reaching the totality in two of the three localities. Semi-structured, open, and free interviews were applied (Albuquerque et al. 2010), followed by ethnobotanical walks and participant observation in daily and community activities (barbecues, rural festivals, meetings, school talks). Topics addressed included: vernacular names, parts consumed, abundance, seasonality, livestock feeding preference, and sites of availability. The work adhered to the Code of Ethics of the International Society of Ethnobiology (ISE, 2006): conversations were recorded with prior consent and transcribed under anonymity codes; testimonies were interpreted from the actors' perspective (Medrano 2012). Twenty herders were interviewed (75% men, mean age 64.3 ± 10.5 years; 25% women, mean age 67.2 ± 8.9 years). Initial contact was made through local referents (justice of the peace, school, neighbors). Walks and participant observation complemented the interviews, providing ecological (vegetation, soil, water) and cultural context (community structure, family ties, land conflicts, land uses).

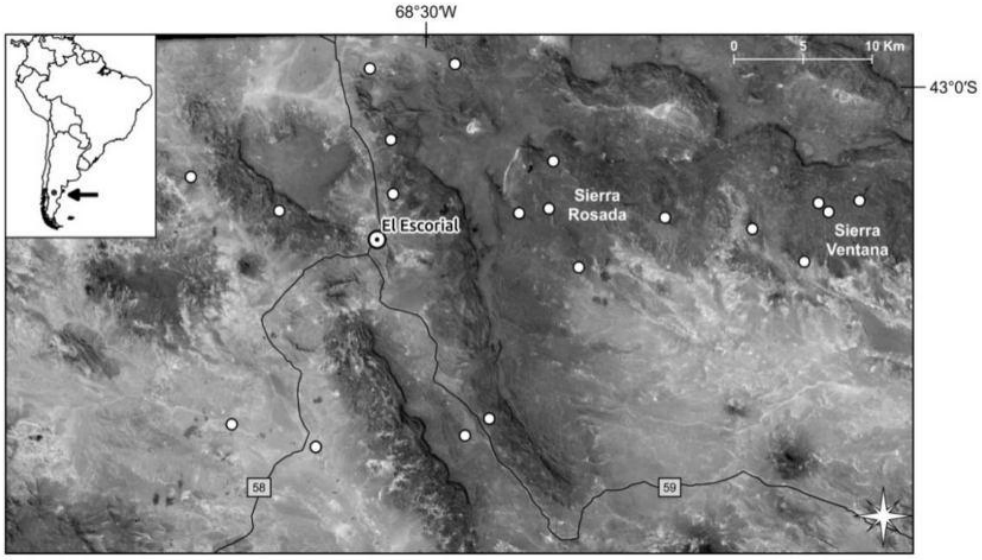


Fig. 1. Map of the study area in the North-Central Plateau of Chubut, Argentina. Visited establishments are shown as white dots.

2.4 Data analysis. Interviews were first analyzed and interpreted qualitatively, considering their emic dimension. To this end, a content analysis of the testimonies was carried out, highlighting common patterns, similarities, and differences that could facilitate the identification of significant elements or themes (Suárez 2009). These were coded and, subsequently, could or could not become interpretation categories. Next, all these categories were grouped for a global analysis, taking into account the frequency with which a topic was referred to by people (Powell et al. 2017). Based on the data processed from the interviews, emic and etic categorizations were made according to their nature. Etic categorized data were analyzed quantitatively. Composition and richness of total species and botanical families were estimated. Recorded species were classified according to their biogeographic origin into native and exotic following Zuloaga & Morrone (1999a,b). Emic categories were: 1) Local valuation (most valued, highly valued, moderately valued, little valued); 2) Season of consumption (spring-summer, all year); 3) Plant part consumed (leaves, flowers, fruits); 4) Sites where available (field, mallín/humid zones). Etic classification categories of species by forage class were also defined, grouping botanical species: non-grass and non-graminoid herbs (H), woody (L), grasses or graminoids (G), and cacti (C). Classification by habit and biogeographic origin was elaborated following the information provided by the Catalog of Vascular Plants of the Southern Cone of the Darwinion Botanical Institute (http://www.darwin.edu.ar/proyectos/floraargentina/fa.htm). Quantitative comparative analyses were carried out through statistical comparisons between categories using the binomial test ($p<0.05$).

3 -Results and discussion

3.1. LEK: classification and integration of forage biodiversity

3.1.1. Forage diversity: Animals live off the field

The results show that forage LEK is structurally anchored in a set of botanical families and forage classes that make up the landscape. This structural anchoring in local biodiversity constitutes a first systemic attribute of LEK, evidencing that it is not knowledge disconnected from the territory, but rather knowledge integrated into its network of ecological relationships.

According to the local view, forage is implicated in animal health: "*...if there is no food, the animal gets sick and dies*" (DD-E). Diseases that, according to the local view, are due to lack of food are also mentioned, such as blindness and changes in animal behavior (Castillo & Ladio, 2019). Considering that no supplemental feeding practices were recorded, livestock raising depends absolutely on wild forage resources.

The ethnobotanical record included 72 species of wild plants belonging to 27 botanical families of forage importance from the local perspective (Online Resource 1). Most are native (87.5%), with only a few exotic species such as *Rosa rubiginosa* and *Bromus tectorum*, among others (12.5%).

From a systematic point of view, local knowledge relies on a core of recurrent botanical families. The main botanical families are Poaceae (16 species), Asteraceae (13), and Fabaceae (8) (Figure 2), coinciding with ethnobotanical research in other Argentine regions (Muiño 2010) and with pastoral systems in Africa and Asia (Naah, 2019; Sharifian et al., 2023). Hence, our record adds to the evidence of a recurring pattern in dry grasslands worldwide.

The local relevance of Poaceae and Fabaceae is consistent with agronomic and nutritional studies that highlight grasses (such as *Jarava neaei*, *Schismus barbatus*, *Poa ligularis*, among others) for their energy contribution: dry matter, fibers, and starch, while Fabaceae (legumes) (such as *Hoffmannseggia trifoliata*, *Neltuma denudans*, among others) stand out for their crude protein content and essential amino acids (Ball et al., 2001). This complementarity, implicit in LEK, is manifested by integrating both knowledge systems. Previous studies have shown that mixtures of grasses with legumes improve forage quality — increasing crude protein and reducing fiber content — which reinforces the importance of family integrality in the studied forage record, as the basis of a sustainable animal health system (Ball et al., 2001).

The case of Asteraceae, on the other hand, differs from the previous ones: being the botanically richest family in the region (Correa, 1971), its presence in the forage ethnobotanical record responds more to its abundance than to specific nutritional qualities, although some species are consumed by livestock in scarcity situations. Similar patterns have been observed in other ethnobotanical studies, where environmental availability influences the forage relevance of a family beyond its nutritional quality (Scarpa, 2007; Sharifian et al., 2023).

On the other hand, when considering the ethnobotanical record according to forage class, we find that it is distributed with a predominance of woody species (46%), followed by grasses or graminoids (26%), non-grass and non-graminoid herbs (25%), and cacti (3%).

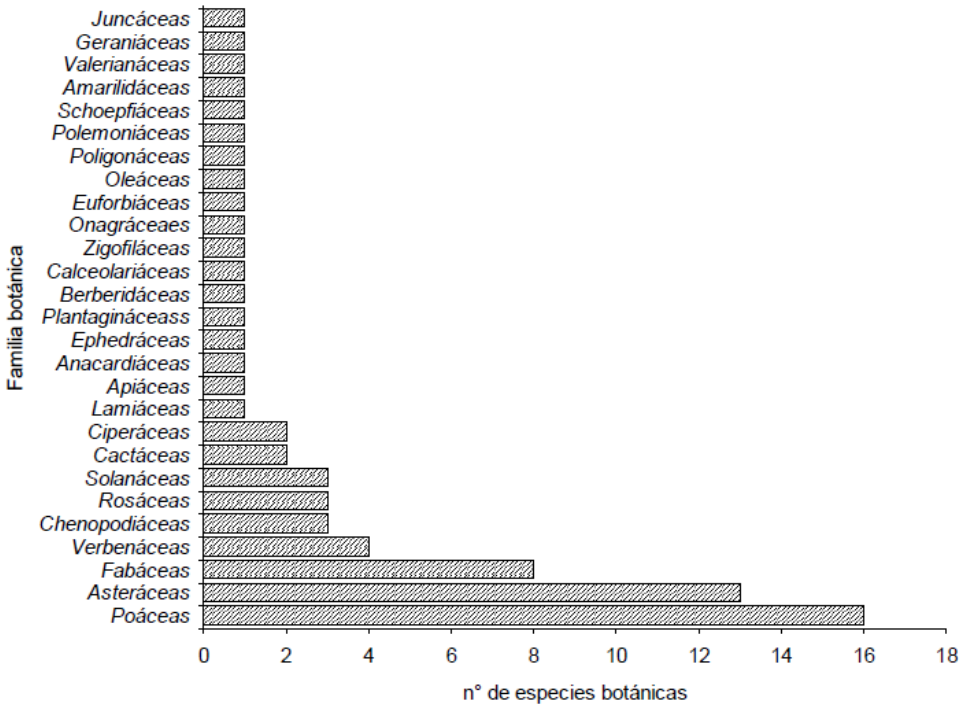


Fig. 2. Botanical families of forage importance that make up Local Ecological Knowledge among rural herders of Northeastern Chubut.

3.2. LEK: processing of environmental information, roles, and interdependencies

Among the results, we found that LEK involves a differential valuation of biodiversity, based on an interpretation of the ecological-productive roles that each component plays in the system, as well as their temporal and spatial interdependencies. The processing of environmental information and the identification of roles and interdependencies constitute a second systemic attribute of LEK.

3.2.1. Differential valuation: nutritional, phenological, and plant-part criteria

Not all plants are equal

Of the 72 species recorded in this work, not all are valued in the same way by herders (Online Resource 1). The results show that species are distinguished according to multiple valuation criteria that respond to the function they fulfill within the pastoral system: nutritional function, stability, or resilience.

The species most sought by animals

Within the etic category "most valued," we found a greater number of citations of plant species belonging to forage classes G (57%) and H (33%) (multinomial test $p<0.05$). In accordance with local knowledge, the importance of grasses and/or graminoids in livestock feeding has been highlighted by Borrelli (2001) due to their high nutritional contribution, as well as in studies where the high proportion of perennial grasses consumed was evidenced through sheep feces analysis in Chubut (Pelliza Sbriller et al. 2005). For example, diet studies in sheep from the region of the western hills and plateaus describe the most consumed grasses as: coirón poa (*Poa ligularis*), coirón dulce (*Festuca pallescens*), and pasto hebra (*Poa lanuginosa*), and tender grasses such as cebadilla (*Bromus sp.*) and cola de zorro (*Hordeum sp.*) (Bran 1986; Pelliza Sbriller et al. 1997). These species, among others, were mentioned during the interviews as "the most consumed" species, thus grouped as "of greatest

value" (Figure 3, Online Resource1). Although pasto salado (*Distichlis spicata*) is also recorded among the most valued grasses in this work, in this case it is highlighted for its abundance and availability in mallines throughout the year, along with junquillo (*Juncus balticus*). Pelliza Sbriller et al. (2005) emphasized the importance of this perennial grass over the rest of the grasses, through diet analysis in sheep from Chubut, due to its presence in edaphic conditions where other grasses have limited or null growth, while also highlighting its capacity to survive overgrazing and aridity. These results indicate that the "most valued" species fulfill a central productive function according to their nutritional values, that is, their valuation is directly associated with their capacity to translate into animal productivity.

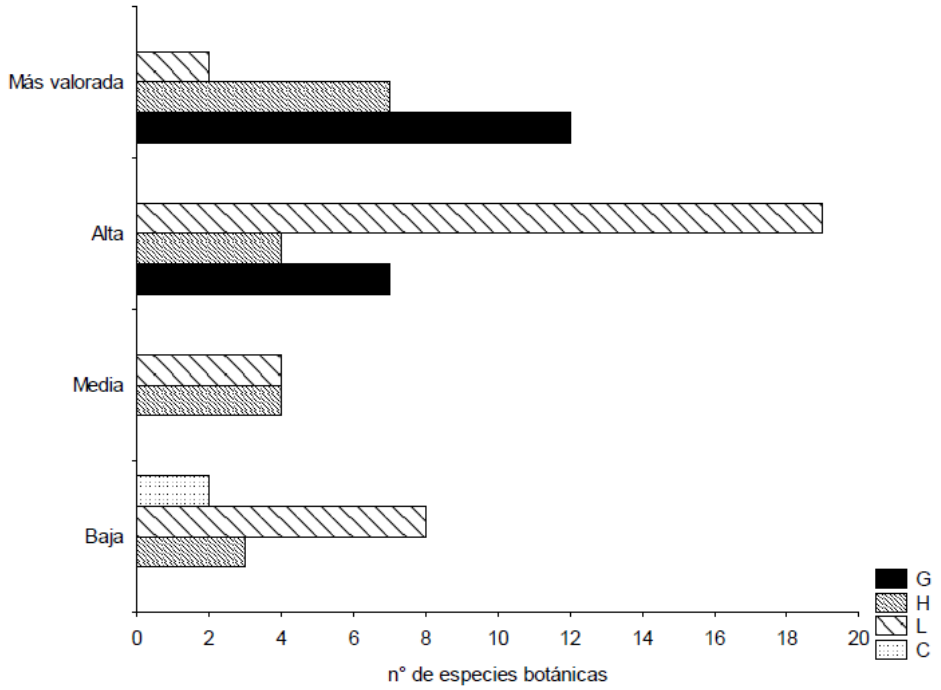


Fig. 3. Differential valuation of the plant resource according to forage class. C: cacti, L: woody, H: non-grass and non-graminoid herbs, G: grasses or graminoids.

Flowers, fruits, shoots, and leaves: how animals use plants

We found that plant species are also valued according to the different parts consumed by livestock. Among them, shoots, flowers, fruits, and leaves are mentioned, each associated with different forms of use and forage value (Online Resource 1).

For example, algarrobillo (Neltuma denudans) stands out: "...The fruit is very fattening..." (PM-E), consistent with its high crude protein content (INTA EEA Bariloche, 1992) and with studies from western Formosa that also highlight the value of fruit-bearing woody species such as *Neltuma alba* and *N. nigra* (Scarpa 2007).

Other species are valued for their "evergreen" leaves, such as zampa (*Atriplex lampa*), with 13% protein but limited digestibility due to salts and fibers (Barría et al., 2017), and yao-yin (*Lycium chilense*), which also has green leaves year-round.

The ethnobotanical record also includes a high animal preference for the flowers of some species that even reveal possible subsequent effects on the perceived quality of livestock products. For example, the flowers of neneo (*Mulinum spinosum*): "*you can already see the animal coming with a yellow*

mouth, it loves eating the flowers, but the animal can't be eaten, no.... the meat has a bitter, ugly taste..." (JG-ST); "*...In February you can't eat the animal because they're full of neneo...*" (AD-E). The high palatability of neneo flowers has been supported in the scientific literature given their nutritional quality, as they have 10.6% crude protein and 64% digestible dry matter (INTA EEA Bariloche 1992). Likewise, "tender shoots" or new growth are mentioned, of species that later reduce their palatability according to their spines and woodiness, such as *Chuquiraga avellaneda*e or *Prosopidastrum globosum* (Online Resource 1).

The differential valuation of plant parts as a LEK criterion has been documented globally. In a review covering 10 countries, Sharifian et al. (2023) identified the indicator 'only parts are eaten' (OPa) as a recurring principle among traditional herders, with special emphasis on the appreciation of fruits from woody species and evergreen leaves.

3.2.2. Temporal processing: seasonality as an organizer of forage roles

Each plant has its moment: the "verdín" and spring resources

Online Resource 1 shows that the valuation that herders attribute to forages varies according to their seasonality. Some species fulfill the role of providing food during the growing season (spring-summer, 56%), while others assume the role of stable support by being available all year (44%).

In spring, annual herbs are mentioned for their particular importance when they become available. According to local views, they grow depending on previous wet seasons (autumn-winter) and are locally called "verdín" (Figure 4), being especially relevant for their attributed role in animal feeding during the reproductive period.

"*...and it depends on the season of the year. For example, in spring there is the verdín, that is good for the animals, for sheep, it helps with milk...*" (DD-E).

That is, the importance attributed to the verdín is not limited to its direct consumption by livestock, but also to its perceived effects on milk production of mothers nursing their young during that season. Also, in late spring and summer, woody species become important, as their shoots, flowers, and fruits become available and are used by animals. The variation of plant functional roles according to seasonality as a central criterion of LEK about forages has been documented globally; in a review covering 12 countries, Sharifian et al. (2023) identified 'seasonal variation' as one of the most recurring indicators among traditional herders.

Thus, seasonality is not merely a phenological datum but an organizing criterion of forage functions, where the same species can assume different roles depending on the time of year.



Fig. 4. a) The spring "verdín" as food for animals. Alfilerillo (*Erodium cicutarium*) forms part of LEK as a species valued as spring forage (Sierra Rosada, November 2013). **b)** Availability of the "evergreen" leaves of zampa (*Atriplex lampa*) and its presence in sites where grasses are scarce (Livestock establishment "Tres Lagunas", José Huaniman, El Escorial area, February 2013).

3.2.3. Spatial processing: complementarity of environments

Between the field and the mallín

Among the results, we found that LEK involves the spatial processing of the landscape, which allows articulating the use of complementary environments.

During the interviews, two main foraging environments were mentioned. The forage plants mentioned (Online Resource 1) come from these two environments: the field (85% of species) and the mallín (15%) (Figure 5, Online Resource 1).

The field is perceived as a multipurpose space, where herders spend most of their time "*campereando*". "*...I like the field... by chance they find me at home...*" (DD-E). Likewise, from a local perspective, it is a key learning space, a dimension that some interviewees consider currently threatened: "*...today's youth know nothing about that because they don't grow up in the field...*" (PM-E).

Through expressions such as "*If good years come, the field returns*" (JG-ST), a vision of contingency regarding grassland recovery is reflected. According to this perspective, the field can recover when humidity accompanies it, although this possibility finds its limits in soil fragility and desertification processes that may be irreversible. This notion "the field returns", far from expressing a naive faith in ecosystem resilience, connects climatic uncertainty with the material limits imposed by soil degradation.

Mallines: water and pastures

Mallines are perceived by herders as highly valued spaces, mainly due to access to water and pastures different from those of the field. This importance is widely recognized: they are wetlands associated with watercourses, of high livestock interest due to their moist soil and palatable pastures (Lloyd, 2002). From the local perspective, the value of the mallín arises from the combination of two resources essential for livestock farming: water and food.

Sheep move freely between both environments, since establishments do not commonly have paddocks: "*...The sheep move from the highest to the lowest parts during the day, seeking their own food and water...*" (DD-E). Old sheep are especially appreciated for family consumption due to their foraging behavior: "*...they are the ones that know how to feed themselves best, they know where the best forages grow...*" (DD-E). Among the interviewees, none buy or produce additional forage; among the arguments mentioned are structural limitations, as well as those linked to animal behavior: "*...the animal gets spoiled and then doesn't leave the corral...*" (PM-E), and "*...driving the flock in times of drought produces significant soil erosion...*" (AI-SR).

The complementarity between both environments is central to the functioning of the system. The field offers mainly woody resources adapted to arid conditions, while mallines concentrate water and pastures highly valued by herders. In this way, the pastoral system is sustained by the articulated use of environments that fulfill different but complementary functions, allowing animals to simultaneously access food resources and water sources in a semi-arid ecological matrix, characterized by marked environmental heterogeneity and seasonal forage deficit.

The differentiated and complementary use of foraging environments has been identified as a global principle of traditional ecological knowledge of herders in various regions of the world. In a recent review, Sharifian et al. (2023) documented that herders from Mongolia, Kenya, Iran, and Hungary recognize and prioritize certain habitats — such as wetlands, meadows, and valleys — for their capacity to provide high-quality forage and water even during scarcity periods. In line with this global finding, herders of the Patagonian plateau give central value to mallines as the support of their productive activity. This valuation acquires particular relevance in a free grazing system, where water availability organizes the daily and seasonal movements of livestock between both environments.

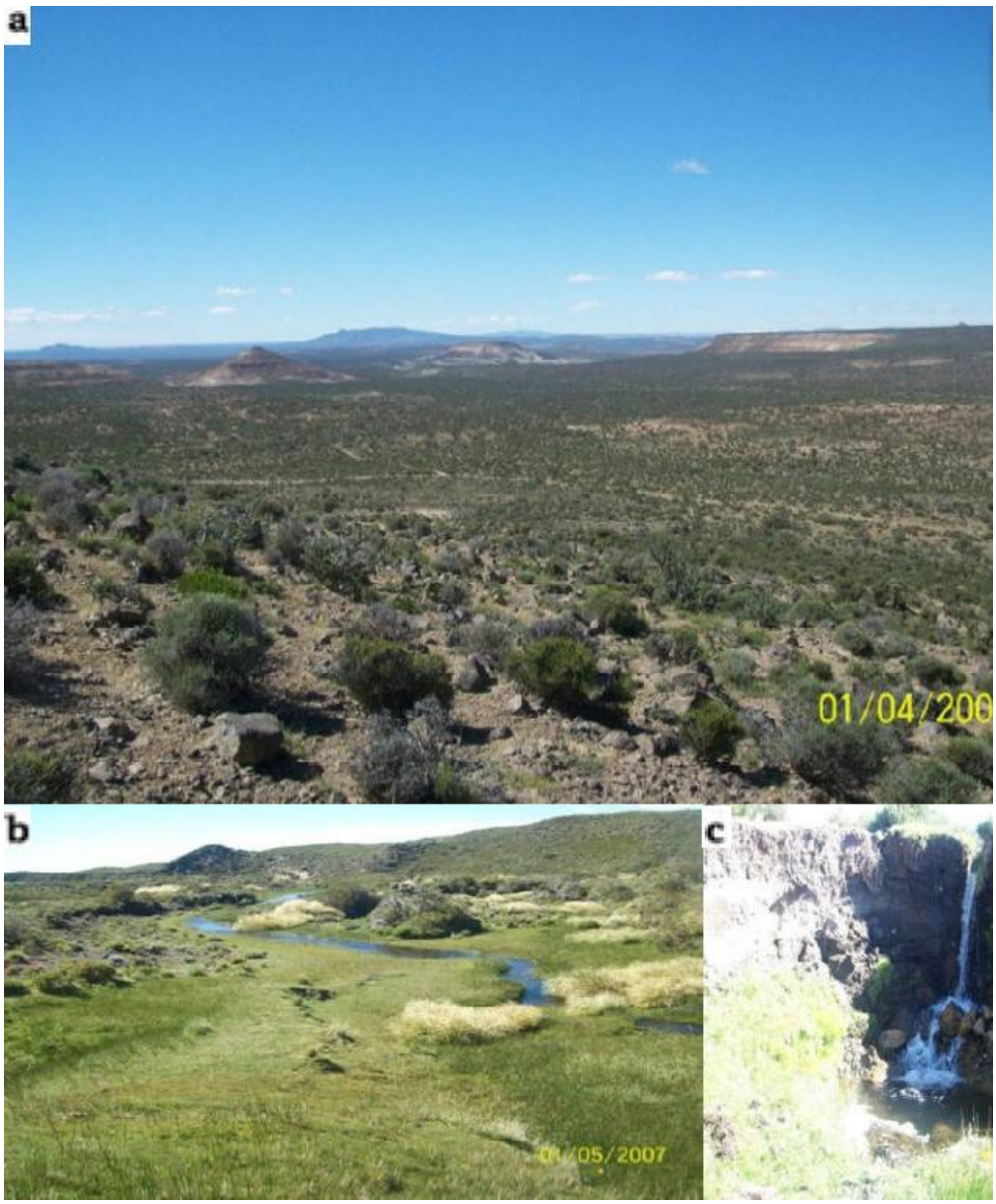


Fig. 5. Both the field and the mallín, or humid zones, represent important environments as a source of "natural" forage for animals. **a)** The field is observed, with a predominance of shrubs and, in the background, the plateau, on the road to Sierra Rosada, April 2014. **b)** and **c)** Rural herders highlight the importance of the mallín as a source of water and food with a greater amount of "pasture". The contrast between the vegetation of the mallín and the field is observed. Cascadita de Sierra Rosada, November 2013.

3.2.4. Identification of stability and resilience roles: woody species and scarcity forage

Here the animal survives thanks to the bushes

The value attributed to certain species does not necessarily derive from their preference or nutritional quality, but from their capacity to sustain animals when preferred resources disappear. Within the etic category "highly valued," we found a greater number of citations of plant species belonging to the woody forage class (63%) (multinomial test $p<0.05$) (Figure 3). Woody species, for example, are highlighted for their permanence and availability in contexts of drought and forage deficit, or for being the ones that are available or the only accessible species.

During conversations, the low availability of "fine pasture" in the fields is emphasized. This deficit situation has been related by interviewees to the environmental situation the region is experiencing, mainly referred to as "drought." According to the local view, it is in situations of forage deficit that shrubby species become important, representing great help due to their availability and playing a fundamental role in animal survival, and therefore in the stability of the system, as for example, Zampa, a species cited for its "evergreen foliage" (*Atriplex lampa*). In the words of a resident: "*...Here the animal survives thanks to the bushes (shrubs)...*" JH-E. Our findings coincide with what was recorded by Scarpa (2007) in western Formosa, who proposes that low pasture availability would explain the preponderance of shrubby vegetation in his forage ethnobotanical records.

Sharifian et al. (2023) documented that woody species represent 30.5% of forage species globally, while in our study they reach 46%, supporting the idea that their importance increases in arid zones (Barría et al., 2017; Sharifian et al., 2023).

In accordance with the above, Nakamatsu (1986) highlights the specific value of woody species in the Patagonian steppe as a forage resource, both for their quantity and quality. Scientific evaluations have recognized the forage contribution of shrubby species, fundamental for adjusting field productivity estimates, which initially focused mostly on grasses (INTA EEA Bariloche, 1992; Pelliza Sbriller et al., 1997). For example, the aforementioned neneo (*Mulinum spinosum*), highly sought after by small livestock, develops spring shoots with high nutritional content (13.5% crude protein and 66.5% digestible dry matter), and its flowers also provide forage value in summer (INTA EEA Bariloche, 1992). Another example cited by interviewees is mamuel choique (*Adesmia campestris*), for which high nutritional values have been recorded, with 18% crude protein in its shoots (INTA EEA Bariloche, 1992). Nutritional analyses of related Patagonian woody species, such as the cited *Adesmia salamancensis* and *Atriplex lampa*, confirm that, although their protein content is moderate (10-13%), they present high digestibility and constitute a relevant forage resource in the region (Barría et al., 2017). According to the above, woody species constitute a predictable and resistant resource against seasonal forage deficit (Barría et al. 2017), which suggests that their strategic valuation could be a recurring principle of traditional knowledge in arid environments (Sharifian et al., 2023).

When pasture is lacking: scarcity forage

Furthermore, herders identify species that, without being preferred, acquire critical importance in times of crisis. In this sense, woody species also represent the only food available during major winter storms, when snow completely covers the vegetation and the animal only has access to the branches of the tallest shrubs. "*...Sometimes you open a sheep and find nothing but sticks in its stomach...*" MM-SV. There is thus a set of "forced consumption species," thanks to which animals "survive" in "bad times." Species such as *Colliguaja integerrima*, *Larrea nitida*, *Grindelia chiloensis* have been grouped as of lower relative valuation (Online Resource 1), species that we probably would not find in conventional scientific forage valuation lists. However, this lower valuation does not imply ecological irrelevance: when the most sought-after resources become unavailable, these species sustain livestock. As a herder expresses: "*When the animal has nothing to eat, it spends its time chewing sticks...*" In accordance with the above, Borrelli (2001) groups shrubby species of low quality but high participation in sheep diet (such as colapiche, *Nassauvia glomerulosa*) within the category of "forced consumption species."

The identification of these species reflects a LEK forged in socio-environmental contexts of recurrent variability and crisis. In a scenario characterized by structural vulnerability, prolonged droughts, and scarce access to external inputs, herding communities have been forced to develop detailed knowledge about those species capable of sustaining livestock under extreme conditions. This knowledge of "scarcity fodder" has been documented in herders from Iran, Mongolia, Kenya, Hungary, and Poland (Sharifian et al., 2023), and our results extend this functional category to semi-arid Patagonia.

Fine-grained ethnoindicators

Herders deploy fine-grained monitoring that extends to detailed temporal scales. For example, quina (*Chenopodium album*) is sought by animals only during the morning: "*...the plant must be that it is hot after midday...*" (JG-ST). In this sense, monitoring is linked to forage availability dynamics, building ethnoindicators of forage scarcity. For example, alfilerillo (*Erodium cicutarium*) is a herb highly sought by animals, but if it is observed that they pull it out by the root, this is indicative of overgrazing and resource depletion; the time sheep take to move between shrubs or the depth of search under branches also denote, for herders, forage deficit (Castillo et al. 2020).

These monitoring logics are crucial in contexts of climatic variability and environmental crises, from which meanings and species valuation criteria are constructed. An example is scarcity forage, identified as that which sustains livestock in droughts or snowstorms — such as *Colliguaja integerrima*, *Larrea nitida*, and *Grindelia chiloensis* —, a category that has been documented in herders from 14 countries (Sharifian et al. 2023) and that here is extended to semi-arid Patagonia. Therefore, this fine-grained knowledge is constructed from a situated reading of environmental variability: the "verdín" is valued for lactation in spring, quina only in the morning, and scarcity forage for winter crises or droughts.

From the above, it follows that palatability, far from reflecting fixed attributes of plants, depends on seasonal context, time of day, and livestock needs, and is influenced by multiple variables — morphology, phenology, chemical composition —. Experimentally, it has been shown that animals can learn to consume plants considered "non-palatable" if they are nutritious and non-toxic, and their preferences change according to their metabolic needs (Burritt 2011; Haq & Badshah 2023).

In line with the above, forage valuation is not a static attribute of species, but is constructed based on context. Naah (2016) reported similar patterns in West Africa, where seasonality and livestock type modulate forage preference, as occurs with *Pennisetum pedicellatum* for cattle in rains and *Arachis hypogaea* for goats and sheep in dry season.

Our findings evidence a logic where livestock adapts to the grassland in a dynamic and reciprocal relationship. Together, these valuation criteria show that LEK operates with a high level of functional precision, integrating temporal and environmental variability into management decisions adjusted to each context. This precision, which is constructed and recreated in daily practice, is a characteristic of adaptive knowledge systems (Chao et al. 2025; Sharifian et al. 2023).

3.3. LEK: regulation and adaptive decision-making

We found that the processing of temporal, spatial, and functional information (Section 2) lays the foundations for the regulatory function of LEK. This regulation is manifested in adaptive management decisions that translate knowledge into concrete actions on the system. This capacity to

translate knowledge into management practices that sustain the system constitutes the third systemic attribute of LEK.

Gathering rams in winter

A local practice that evidences productive regulation is the separation of rams (male sheep) from ewes, in order to bring them together in winter so that births coincide with periods of greatest forage abundance, thus promoting the health of mothers, milk production, and the survival of offspring. According to local logics, spring births are favored by greater forage abundance: grasses change color, turn green from winter humidity, and flowers and annual plants appear, all species that fulfill specific roles in livestock feeding, such as milk production.

In this way, reproductive management decisions are closely linked to the interpretation of the seasonal dynamics of vegetation. Similar practices have been documented among herders in Mongolia, where the synchronization of reproductive cycles with forage productivity peaks has been documented as a central resilience strategy (Fernández-Giménez, 2000).

Likewise, monitoring the consumption of woody species and scarcity forage (such as the identification of key species like *Atriplex lampa*) that LEK involves can guide management decisions, anticipate critical periods, or make adjustments — reducing stocking rates, mobility — to avoid overgrazing. This knowledge about livestock foraging behavior in stress contexts evidences the regulatory bases of LEK, which aims to sustain productivity and preserve the ecological base of the system. Furthermore, although the absence of external forage supplements (they do not buy or produce additional forage) has been mainly associated with structural deficiencies (such as the lack of storage structures) by interviewees, they also express LEK foundations: "*...the animal gets spoiled and then doesn't leave the corral...*" (PM-E), and "*...driving the flock in times of drought produces significant soil erosion...*" (AI-SR). Together, productive regulation and adaptive regulation operate complementarily and make up LEK. While the former optimizes system performance, the latter sustains it in times of crisis, allowing its persistence in the face of environmental variability.

3.4. LEK as a central operational component of the pastoral system

From an analytical perspective, forage LEK reflects an integral, biodiverse, dynamic, and staggered vision, organized around ecological and productive functions. LEK translates and processes environmental information into adaptive management decisions, integrating the functional components listed in Table 1.

Throughout the interviews, plants were recurrently associated with specific roles within the system, highlighting species that can be considered emblematic resources of such roles. Table 1 shows a functional interpretation of the roles that have been identified and valued by herders for the different components surveyed in the system. Some species fulfill productive functions linked to lactation and fattening; others provide flowers, fruits, leaves, or shoots consumed at particular times of the year; woody species, in turn, act as stability and resilience resources, sustaining livestock during periods of scarcity and extreme climatic events.

3.4.1. Functions and contextual roles of system components

The importance attributed to woody species constitutes a particularly illustrative example of this functional organization (Table 1, Diagram 1). Although many of them do not integrate the set of species considered of highest forage quality, they are valued for the diversity of functions they fulfill:

they provide shoots, flowers, leaves, or fruits at different times of the year, remain available when herbaceous resources decrease, and in situations of drought or intense snowstorms, can become the only food accessible to animals. Their relevance, therefore, does not depend exclusively on their nutritional quality, but on their position within the functional organization of the system.

The same functional logic is observed in foraging environments (Table 1). The field and the mallín do not constitute simply different spatial units, but complementary environments that provide different resources to the system. While the field provides mainly woody species adapted to arid conditions, mallines concentrate water and pastures highly valued by herders. The free mobility of livestock between both environments allows articulating these resources within a feeding strategy that takes advantage of the environmental heterogeneity of the steppe.

That is, the relevance of a plant is contextual and dynamic, depending on its contribution to processes such as lactation, animal maintenance, survival during critical periods, water provision, or food availability at different times of the year. The same species can assume different functions according to the environment or season, while different species can contribute to similar functions within the system. This logic shifts the focus from isolated species to the functions and relationships that sustain the integral functioning of the pastoral system (Table 1).

This interpretation is in accordance with recent approaches that have proposed integrating multiple ecological and use attributes to evaluate the forage value of species (Jiménez-Escobar et al., 2026) through the ranking of species based on the combination of different criteria. In this sense, the importance of a plant does not depend exclusively on intrinsic attributes such as its quality, availability, or preference, but also on the functions it performs within specific ecological and productive configurations.

These characteristics of LEK — its capacity to integrate the functional components listed in Table 1 and translate them into management decisions — are key in arid socio-ecosystems characterized by high climatic variability, whose high unpredictability is associated with risky production (Easdale & Aguiar 2012).

Table 1. Functional components of the pastoral system identified from local ecological knowledge, and their contribution to emergent properties of productivity, stability, and resilience (see Diagram 1)

Functional component from a local perspective	**Description**	**Role attributed within the pastoral system from a local perspective**	**Agroecosystem functionality**	**Key species (representative examples)**
Spring "verdín"	Tender spring herbs	Favors lactation and offspring growth.	Production and reproduction	Alfilerillo (*Erodium cicutarium*), coirón poa (*Poa ligularis*), tender spring grasses (various species)
Fine or	Resources highly	High forage	Productivity	Coirón poa (*Poa*

preferred pastures	sought by livestock	quality.		*ligularis*), coirón dulce (*Pappostipa humilis*), pasto hebra (*Pappostipa speciosa*)
Permanent woody species	Shrubs available most of the year	Maintain food when pastures are lacking.	Stability	Zampa (*Atriplex lampa*), yao-yin (*Lycium chilense*), mamuel choique (*Adesmia campestris*), neneo (*Mulinum spinosum*)
Specific resources	Fruits or parts associated with fattening	Energy or nutritional contribution. Increase body condition.	Productivity	Fruits of algarrobillo (*Neltuma denudans*), fruits of barba de chivo (*Prosopidastrum globosum*)
Strategic environments (mallines)	Water and pastures	Access to water and quality forage.	Spatial complementarity	Mallines with junquillo (*Juncus balticus*) and pasto salado (*Distichlis spicata*)
Scarcity forage	Resources used in droughts or snowstorms	Sustain livestock in critical situations.	Resilience	Jarilla (*Larrea nitida*), palo azul (*Colliguaja integerrima*), grindelia (*Grindelia chiloensis*), colapiche (*Nassauvia glomerulosa*)
Adaptive management practices	Adjustment of management to resource cycles	Synchronization of births and forage availability.	Production–resource coupling	Spring births; differential use of field and mallín

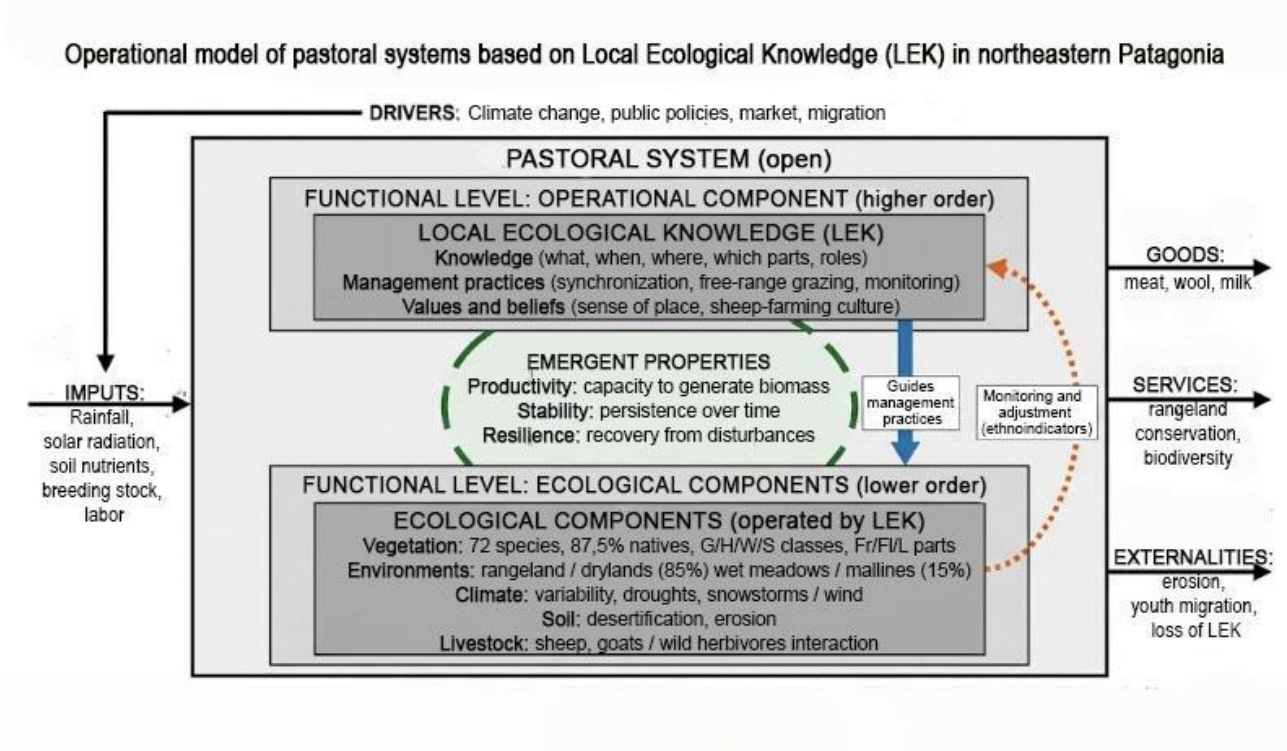


Diagram 1. Operational model of pastoral systems based on Local Ecological Knowledge (LEK) in northeastern Patagonia. Arrows represent flows of information, decision-making, and matter. Functional levels indicate a systemic hierarchy: LEK operates (organizes, regulates, drives) ecological components. Emergent properties arise from the interaction between both levels. Based on ethnobotanical fieldwork. G: Graminoids, H: Herbs, W: Woody, S: Shrubs. Fr: fruits, Fl: flowers, L: leaves.

3.4.2. LEK as an irreplaceable operational component: proposing the Pastoral Agroecosystem Framework (PAF)

Following the agroecological systems approach (Tittonell, 2020), the pastoral agroecosystem can be understood as a set of nested subsystems that interact to generate productive and ecological functions. Throughout the preceding sections, we have shown that the LEK of Patagonian herders presents three systemic attributes: (1) it is structurally anchored in local biodiversity and its network of relationships; (2) it attributes ecological-productive roles to system components and interdependencies in the spatial and temporal dimensions; and (3) it articulates and regulates the system through adaptive management decisions. This systemic character gives rise to emergent properties linked to the productivity, stability, and resilience of the system (Diagram 2; Table 1).

In this work, we propose an analytical distinction between two levels of functionality. On the one hand, the functional components we have identified (Table 1) — plant resources, environments, practices — constitute the ecological structure of the system that is operated. On the other hand, LEK constitutes the higher-order operational component that operates on that base and represents the management and decision-making subsystem (Tittonell, 2020). Since LEK fulfills an operator role — it identifies, articulates, and regulates the components of the first level — it constitutes a central and irreplaceable operational component of the pastoral system.

Based on the above, we propose the Pastoral Agroecosystem Framework (PAF):

In the context of pastoral agroecosystems, Local Ecological Knowledge is defined as a dynamic set of knowledge, practices, beliefs, and values, transmitted and re-signified over generations and through livestock production practice, constituting a higher-order systemic operational component that identifies, monitors, regulates, and articulates the functional components of the agroecosystem, operating through adaptive management decisions.LEK, as part of the socio-ecological network and subject to ecological, climatic, historical, and territorial forces, promotes emergent properties such as productivity, stability, and resilience by integrating spatial heterogeneity, seasonality, and crisis dynamics into the decision-making process (Diagram 1).

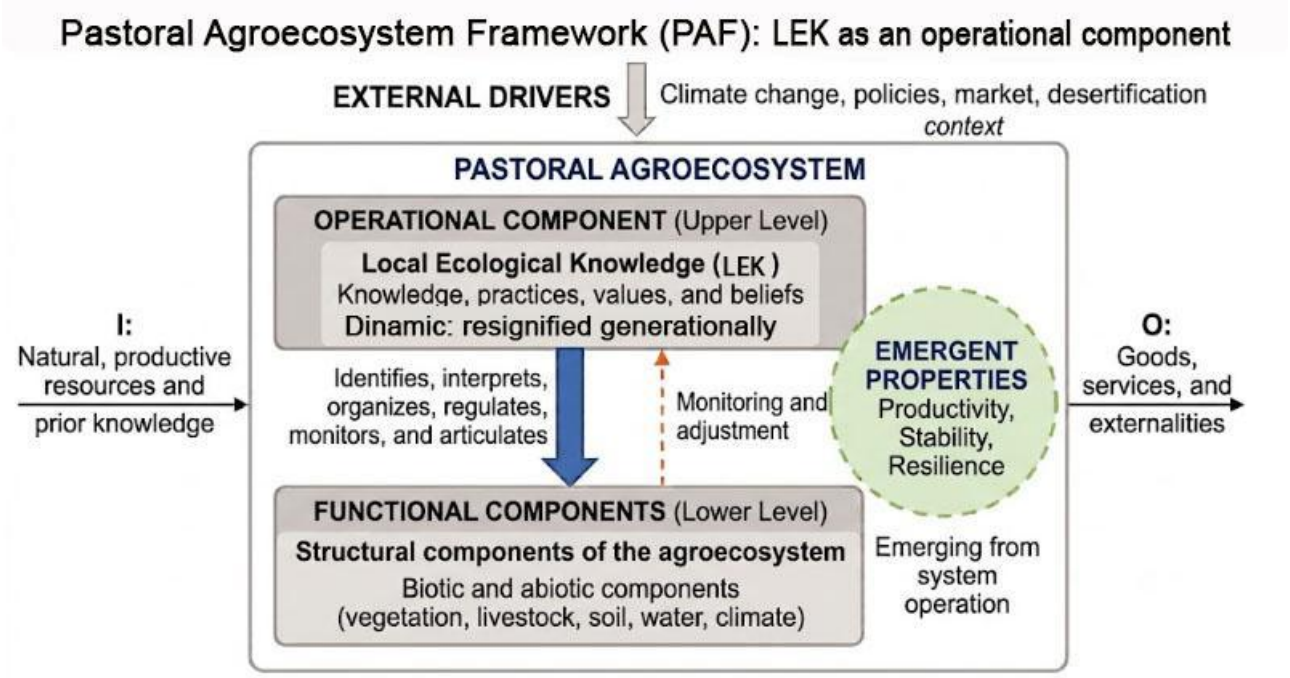


Diagram 2. Pastoral Agroecosystem Framework (PAF). The diagram represents the hierarchy of system functionality: Local Ecological Knowledge (LEK) operates as a higher-order operational component that identifies, interprets, organizes, regulates, monitors, and articulates the functional components of the agroecosystem (biotic and abiotic). This operation, mediated by management decisions and feedback from monitoring, promotes the emergence of systemic properties such as productivity, stability, and resilience. Continuous arrows indicate operational flows; dotted arrows indicate feedback. I: inputs, O: outputs.

The definition of LEK as a higher-order operational component in pastoral agroecosystems constitutes a central contribution of this work. Unlike approaches that reduce it to an inventory of knowledge or a set of practices, this definition conceives LEK as part of a network of socio-ecological relationships and proposes that LEK interweaves, organizes, regulates, and articulates the functional components of the system, operating through management decisions that promote emergent properties such as productivity, stability, and resilience. This operation is inscribed in a network of ecological, climatic, historical, and territorial forces that condition and exceed it, and that LEK interprets and translates into situated decisions.

Our work advances by proposing that LEK not only describes, but operates the system. This perspective dialogues with recent studies in family farming systems of Patagonia, which show that LEK translates into concrete management practices, such as the tolerance practices documented by Grimaldi et al. (2024) for the management of harmful arthropods. In doing so, LEK reveals itself not

as knowledge that dominates nature, but as a node in a network of socio-ecological relationships where the human being is one more thread of the fabric.

In our case study, the identification of forage classes (G/H/L/C), the recognition of field-mallín complementarity, the discrimination of plant parts, and the categorization of scarcity forage are evidence that herders do not classify plants by their taxonomy, but by their function within the system. These functional components constitute the 'toolbox' that LEK operates to make management decisions, integrating spatial heterogeneity, seasonality, and crisis dynamics, which allows LEK to sustain the system and promote emergent properties such as productivity, stability, and resilience.

This empirical evidence supports the framework proposed here: LEK is not auxiliary knowledge, but an active factor in the sustainability of the agroecosystem, especially in arid zones with high environmental variability and structural vulnerability.

4. Conclusions

This study documented Local Ecological Knowledge (LEK) about forage plants among herders of the central plateau of Chubut, recording 72 species belonging to 27 botanical families. Herders organize forage through a functional perspective of complementary ecological and productive roles, integrating information on diversity, environments, seasonality, animal behavior, and management practices, evidencing the complexity and systemic character of local LEK.

Based on this empirical basis, we propose the Pastoral Agroecosystem Framework (PAF) based on an analytical distinction between two levels of functionality in pastoral agroecosystems. On the one hand, the functional components of the system — plant resources (forage classes, plant parts), environments (field and mallín), and management practices — constitute the socio-ecological structure of the system. On the other hand, LEK constitutes the operational component that operates on that structure, identifying, monitoring, regulating, and articulating the functional components through adaptive management decisions.

Thus, LEK in pastoral agroecosystems is revealed as a higher-order operational component that organizes, regulates, and articulates the functional components of the system, promoting emergent properties such as productivity, stability, and resilience. The PAF, grounded in empirical evidence, constitutes the central contribution of this work.

This study evidences that the herding production system is sustained by inseparable interrelations between native plant biodiversity, wetlands (mallines) as strategic sources of water and forage, and situated LEK. Consequently, the sustainability of these three components is an ecological and productive condition for the continuity and resilience of these socio-ecosystems in the face of climatic variability, desertification, and other global transformations.

The PAF can guide the design of grassland management policies and support for family farming in Patagonia, essential for development with identity and the reduction of vulnerability to global change, orienting policies toward the "good living" of herding communities (Acosta, 2009).

Future studies could explore the applicability of this operational model in other pastoral agroecosystems of arid zones, as well as deepen the mechanisms of LEK transmission and the factors that favor or limit its operational capacity in contexts of global change.

5. Statements and Declarations

Competing Interests. The authors have no relevant financial or non-financial interests to disclose.

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Ethics statement: The authors confirm that this manuscript complies with the ethical standards of the journal. The work is original, has not been published previously in any form or language, and is not under consideration for publication elsewhere. Any reuse of previously published material has been appropriately acknowledged.

Consent to participate: This study was conducted in accordance with the ethical recommendations of the Latin American Society of Ethnobiology (SOLAE). Prior informed consent was obtained from all individual participants included in the study.

Consent to publish: The authors affirm that human research participants provided informed consent for publication

Data Availability. The datasets generated and analysed during the current study are not publicly available due to confidentiality of participant interviews, but are available from the corresponding author on reasonable request.

Authors' Contributions. L.C.: conceptualization, methodology, fieldwork, data analysis, writing – original draft. A.L.: conceptualization, methodology, data analysis, supervision, writing – review and editing. All authors read and approved the final manuscript.

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